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EFFECT OF FAILURE AND REPAIR RATES ON GAS TURBINE SYSTEM RELIABILITY AND AVAILABILITY

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AbstractIn this work, a reliability and availability analysis program was developed for calculating and monitoring failure rate and repair rate, and how these affect gas turbine power plants' availability and reliability. The program utilized four principal parameters, namely; number of failures, downtime, mean time to repair (MTTR) and mean time between failures (MTBF) in calculating the failure rate, repair rate, availability and reliability of the gas turbines and displaying the outcomes in charts and graphs for clearer understanding. Mathematical relations of notable models were utilized for developing this program. Analysis obtained from this research revealed that increase in failure rate of gas turbine power plants results in decrease in its reliability and availability. Also, repair rate was observed to have same inverse relationship with the gas turbine systems availability. However, effective maintenance management is essential in reducing the adverse effect of equipment failure. This was done by accurately predicting the equipment failure such that appropriate actions can be planned and taken in order to minimize the impact of equipment failure on operation. Downtime losses and maintenance cost of a gas turbine power plant can be reduced by adopting a proper mix of maintenance and repair strategies.

Keywords: Reliability, Availability, Failure rate, Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), Gas Turbine Power Plant, Gas Turbine Reliability and Availability Analyzer (GT-RAA).

1. Introduction

Reliability is the feature of an asset given as a probability that it will perform its required duties within acceptable levels for a given time period. Reliability study is as old as the invention of machines by man. Machines and equipment are indispensable part of our daily lives which makes life easy, comfortable and allows us to overcome huge challenges within a limited time. Man invented machines when they sort for better ways of doing more work with minimal effort. Man started with tools and farm gadgets, followed by the development of simple machines like levers, screws and pulleys, and later, complex machines like the gas turbine. These machine developmental stages had their peculiar challenges with utilization. In the olden days when horses and carts, machetes and hoes, and other simple machines were the order of the day, they were used to do works such as farm works, travel long distances, for harvesting and conveying farm crop yields from farmlands to houses, bans and markets, etc.

After works, these equipment will be cleaned, polished, sharpened and the livestock will be refreshed with food, water and rest. These things were done to maintain its usefulness, availability and dependency (reliability) when needed next time. This occurrence also applies to our modern day use of machines in industries, which require adequate care to maintain its effectiveness, efficiency and reliability. It is pertinent to state here that we can utilize machines without compromising its integrity. This is achieved by accurately planning to stabilize its reliability as the need arises through maintenance, upgrade and monitoring of the equipment. Doing this has several advantages such as reducing unscheduled downtime, extend equipment's life, increase production, transition from "run to failure" to proactive lifestyle and most importantly, improve equipment reliability. However, negligence to machine maintenance and reliability monitoring has being a major concern to Nigerian power sector, which led to reduction in production levels, excessive expenditure, equipment failure, and downtime in production which has crippled our economy, industrial development and drove investors. This study is carried out to solve problems on reliability, availability and maintainability of mechanical equipment in gas turbine power plants while in working condition.

1.1. Gas Turbine Power Plants Performance Overview

The four elements used in determining the performance of any power plant are: functional needs satisfaction ability, ability to make effective use of supplied energy, dependability (reliability) to start and operate optimally, and ability to quickly go back to service after each failure. The design, maintenance, operation and planning of thermal power plants all over the world have recognized the use of reliability analysis as a generally accepted tool in its performance studies (Obodeh and Esabunor, 2011). The main objective of a gas turbine power plant is to provide electrical energy (power), mechanical energy and heat energy to the large consumers in a very efficient, effective and economical way that assures continuity and quality in service. The service quality can be assessed by the availability of electricity to the customers at a normal domestic and industrial voltage and frequency, and other energies like mechanical and heat that can be produced from it. Electricity (power) supply can be reliable when there is continuous supply to customers at standard ranges of voltage and frequency (Wang et al., 2002; Wang and Billinton, 2003; Sikos and Klemeš, 2010).

A modern gas turbine power plant is gigantic, multifaceted, highly cohesive and very huge. For better analyses of the system, it is divided into groups made up of subsystems and functional areas like generation, transmission and distribution (Gupta and Tewari, 2009; Kuo and Zuo, 2003; Lakhoua, 2009). System reliabilities are analysed in individual functional areas and also in combination of all the functional areas. But, for this study it is restricted only to the generation reliability analysis evaluation. The main focus of generation reliability analysis is geared towards the reliability of the generating plants (generators) in a complete gas turbine power plant that produces electric power from primary conversion process of fuel to electricity before it is transmitted.

Under the generation subsystem, reliability is looked at in two ways; adequacy and security (Hooshmand et al., 2009; Valdma et al., 2007). To have a system adequacy at all times, availability of enough working generating units within the system is necessary to enable the system satisfy load demands of the consumers, limitations in system operation and maintenance plan. Security of the system deals with responding to systems disturbances coming from the system. Therefore, Security of the system is linked with reply of the system to whatever disturbances it is exposed to. Again, this work will only deal with the generation system adequacy and not security of the system. In the assessment of the generation system, the whole generating units of the system is surveyed to ascertain its total capacity to successfully satisfy the entire system load demand. This study is sometimes regarded as making system adequacy evaluation. In the assessment of generating system adequacies, transmission system is ignored and treated as single point load (Valdma et al., 2007).

The two main reasons for doing assessment of the generating system is to determine the capacity requirement of the units under generation systems, the system's ability to adequately satisfy demands and to mitigate for the systems planned and emergency outages of power (Oyedepo, et al, 2015).

For the past twenty years, power sector restructuring, renaming and abandoning of the former unregulated model which over took the running of electric energy in Nigeria has been in the forefront (Obodeh and Isaac, 2011). The current "deregulated" plan and policies of the government is structured on the bases of principle of free market, preferring competition amongst participating private partners and new participants playing in the power sector market like the Independent Power Producers (IPPs) and National Integrated Power Projects (NIPPs) and choices of customers. This new structural policies and plan will enable every company generating power to make its own assessment of reliability and pricing relative to generation so that consumers are satisfied (Obodeh and Esabunor, 2011). One such organization that generates power for the national grid is Transcorp Power Limited, Ughelli, Delta State, which is used as a case study for this research. Power Holding Company of Nigeria (PHCN), before now, has been in the forefront of power supply to many consumers, but their supply has been so unreliable because of its many outages. To this, the way forward is to assure plant reliability and economic efficiency so as to improve supply and utilization ratio (Kucherov and Kitushin, 2005). Competitiveness of the market, demand increase from the consumers and recent governmental policy on deregulation of the Nigerian electricity supply sector are creating rivalry amongst the IPPs. To be in the market and survive, suppliers must maintain increased reliability levels, prioritize maintenance actions and reduce maintenance cost (Obodeh and Esabunor, 2011).

2. Research Methodology

The reliability indices needed for this study was provided by personnel in Efficiency and Reliability unit of Transcorp Power Ltd Ughelli, Delta State, Nigeria.

2.2. Data Analysis Procedure

The success of this research work is pegged on the availability of statistical data from the target company of case study and the knowledge of the following theories and models.

2.2.1: Mean Time Between Failure (MTBF)

This is the average period of time an asset will deliver its expected services at an acceptable standard before failing unexpectedly. The measurement is done by testing the system for a total number of periods denoted as 'T' on 'N' number of faults that happens. After testing and repair is done the system is put back to service. However, the time taken for repairs is not included in the total number of test time 'T'. MTBF is then given as equation below

$$\text{MTBF} = \frac{T}{N} \text{ (hours)} \quad \textbf{(1)}$$

Errors are not excluded in this sampling since the observation is only on a portion of the samples total life. Conclusions from the result should permit for these errors. The system that has the biggest MTBF stands as the most reliable.

$$\text{MTBF} = \frac{1}{F} \quad \textbf{(2)}$$

Where: F = expected failure rate.

2.2.2: Frequency of Failure or Failure Rate (F)

The above defines the number of faults recorded per unit time. System having uniform failure rate for most part their working life idealistically, has its failure rate as the reciprocal of their MTBF.

$$\text{F} = \frac{N}{T} \quad \textbf{(3)}$$

Where:

N = Number of failures in between maintenance periods.

T = total operating time in between maintenances.

Also, $\text{F} = \frac{1}{MTBF}$ (faults/hour) **(4)**

In the equations above the repair time for units or components that failed have not been reflected. This short-coming above is a deficiency that cannot be over looked, since there could period when repair time is short and desired more than MTBF. Hence a better model of reliability that considered the time of repair is needed.

2.2.3. Mean Time To Repair (MTTR)

When equipment fails, the time it takes to bring it back to normal working condition on average is called MTTR.

$$\text{MTTR} = \frac{\psi_t}{\emptyset_n} \quad \textbf{(5)}$$

Where:

ψ_t = total outage hours per year.

$\emptyset_n$ = No. of failure per year

Also, $$\text{MTTR} = \frac{1}{\mu} \quad \textbf{(6)}$$

Where:

μ = expected repair rate.

$$\therefore \ \mu = \frac{1}{MTTR} \quad \textbf{(7)}$$

2.2.4: Maintainability

Maintainability is the probability that a system will be restored to operational effectiveness within a given period of time when the maintenance action is performed in accordance with prescribed procedures (Iniyan, 2012).

2.2.5: Availability (A)

Availability is the measure of time equipment will perform its specified functions at an acceptable quality level. Considering a turbine in a power plant, the availability can be defined as the measure of the element of time that it is generating an acceptable power output. This is calculated by dividing every time in a given period into two groups, which are:

(a) Up Time denoted with 'UT': Machine in good working condition.

b) Down Time denoted 'DT': Machine is faulty or is being repaired.

The sum of observation period is given as 'UT + DT'. The Availability or Up time ratio becomes:

$$A = \frac{UT}{UT+DT} \quad \textbf{(8)}$$

$$A = \frac{\mu}{\mu + F} \quad \textbf{(9)}$$

Or,

$$A = \frac{1}{1+F(MTTR)} \quad \textbf{(10)}$$

Using equations (3.2) and (3.6) in equation (3.10), we have

$$A = \frac{MTBF}{MTBF + MTTR} \quad \textbf{(11)}$$

And $$\bar{A} = \frac{MTTR}{MTBF + MTTR} \quad \textbf{(12)}$$

Where $\bar{A}$ = unavailability

Equations (3.11) and (3.12) are particular to systems working within their prescribed life span that is systems with a uniform failure rate. Another representation for the availability is done using failure rate (F) and repair rate (μ) as:

$$A = \frac{1/F}{1/F + 1/\mu} = \frac{\mu}{\mu+F} \quad \textbf{(13)}$$

And $$\bar{A} = \frac{1/\mu}{1/F + 1/\mu} = \frac{F}{F + \mu} \quad \textbf{(14)}$$

In power generating systems on the other hand, unavailability is gotten through a method known as the Forced Outage Rate (FOR), which is described as Forced Outage Hours (FOH) divided by the sum of the Forced Outage Hours and the In-Service Hours (ISH).

$$FOR = \frac{FOH}{FOH+ISH} \quad \textbf{(15)}$$

2.2.6: Availability Factor (AF)

In a mixed system, there are constraints in the nature sectional reliability study has. For that, an introduction of reliability index called availability factor (AF) is used. This is expressed as the ratio of available capacity (AC) to the installed capacity (IC) of the generating unit.

i.e. $$\text{AF} = \frac{AC}{IC} \quad \textbf{(16)}$$

The available generating capacity may be less than the installed generating capacity by the capacity of generating units on outage because of fault or maintenance, then the index becomes adequate. This index cumulatively therefore offers an amount of the probability of a station accomplishing its projected function.

2.2.7: Reliability ($R_{(t)}$)

The ability of performing its required function satisfactorily under any given condition during any given period of time is known as reliability (Ireson et al., 1996). Again reliability can further be defined as the likelihood that equipment is operating without failure in given time period (Obodeh and Esabunor, 2011).

$$\boldsymbol{R_{(t)}} = e^{-\frac{t}{MTBF}} \quad \textbf{(17)}$$

Using equation (3.2) in equation (3.17), we have

$$\boldsymbol{R_{(t)}} = e^{-Ft} \quad \textbf{(18)}$$

Where; t = specified period of failure-free operation

2.3: Evaluation of Reliability Index

Reliability indices could be examined under absolute or relative form of evaluation. In the use of an index in absolute form, a governing standard should be stated for the index at the beginning to determine whether it is passing or failing. In the relative use of an index, different systems are made to use the index and are compared for better analysis.

2.3.1: Systems Relative Reliability Index Evaluation

The reliability index evaluation of gas turbines in relative form is performed when system configuration or arrangement is considered. Systems are either arranged in series or parallel.

2.3.2: Systems in Series

In a series system configuration, when one system fails the entire system fails as well. A series system is one that is as fragile as its sub-system that has fragile link. Hypothetically, this means that 'when a system records "Success", this means that every individual component recorded Success.

$R_{(s)} = R_1 \times R_2 \times ... R_n$ (For component reliabilities variance or) **(19)**

$R_{(s)} = [R_i]n$ (if all i = 1, ... , n components are similar) **(20)**

2.3.3: Systems in Parallel

A system is in parallel when the system can still work provided that the entire component units of it did not fail. Mathematically, the total system reliability is always higher than the reliability of each of its component or sub system.

$R_{(s)} = 1 - (1 - R_i) = 1-(1 - R_1) \times (1 - R_2) \times ... (1 - R_n)$; For component reliabilities variance, or **(21)**

$R_{(s)} = 1 - (1 - R_i) = 1-[1 - R]^n$; if all "n" components are similar; that is, $[R_i = R$; i = 1, ..., n] **(22)**

$R_{(s)} = 1 -(1 - R_1)\times(1 - R_2)\times(1 - R_3) = R_1 + R_2 + R_3 - R_1R_2 - R_1R_3 - R_2R_3 + R_1R_2R_3$ or **(23)**

$R_{(s)} = 1 - (1 - R)\times(1 - R)\times(1 - R) = 3R - 3R^2 + R^3$ (This is when all the components are alike): R_i= R; i = 1, ..., n **(24)**

3: Software Development

Software, Gas Turbine Reliability and Availability Analyzer (GT-RAA) was developed for this analysis. GT-RAA is a web based applications which has front end and back end. A web based application is an application designed to run using a web browser as the application's user interface. The GT-RAA was designed using the following software: PHP, HTML, CSS, JavaScript, Photoshop, and MySQL. These software are further classified into client side, database design and server side design software.

HTML, CSS, JavaScript and Photoshop are classified as client side software. PHP is classified as server side software. MySQL is classified as database design and management system.

The client side software was used in the design of the user interface like the login page and other data input and output pages.

3.1: Development of Flowchart

Flowcharts were used in designing and documenting these programs. Flow chart has many types, but each one has its own sign and styles of boxes and conventional notations. For the flow chart in this work, the two types of boxes used are:

(i) Box type called - A rectangular box type - Which is a processing step, usually called activity step,

(ii) Box type called - A diamond box type - a decision step.

A sample of the flowchart used in development of this program is shown in figure 1 below.

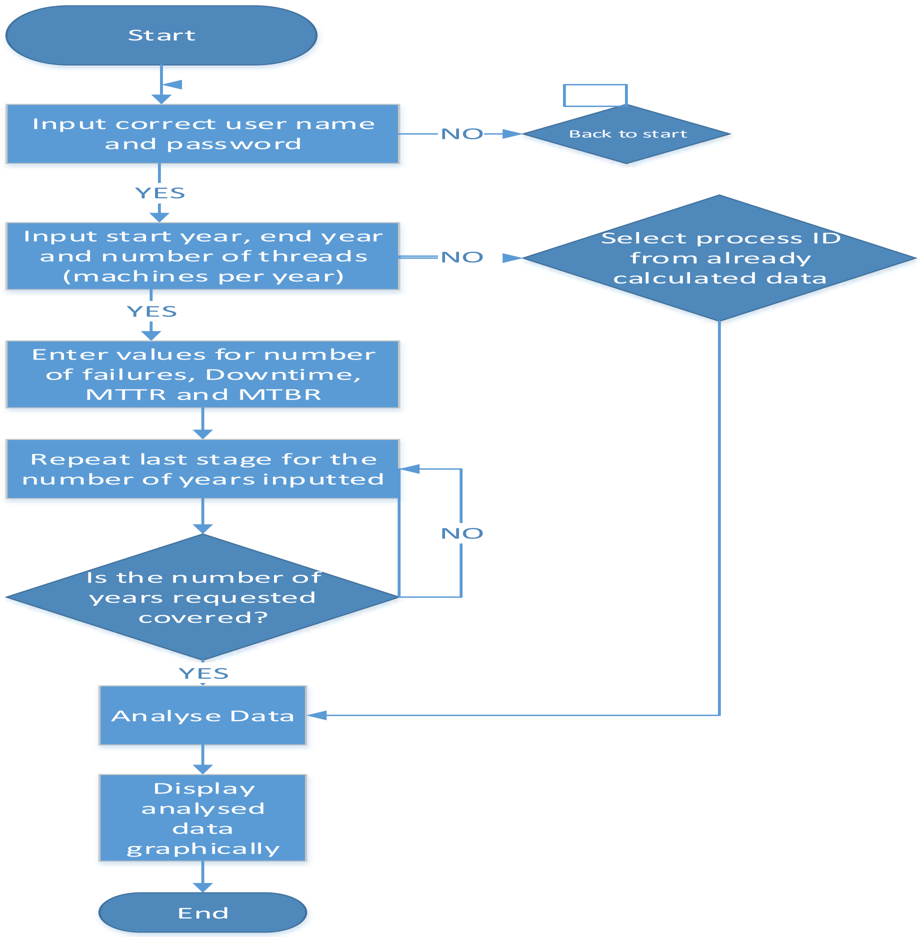


Figure 1: Program flowchart

3.2: Development of Algorithm

An algorithm is a formula for solving problems, centred on conducting a sequence of definite actions. For GT-RAA development, an algorithm was used to state clearly, the stepwise procedure and tolerable limit of values for each step of data input in line with the flowchart.

3.3: Reliability Indices

The summary of reliability indices of Transcorp Power Ltd Ughelli, Delta State, Nigeria for the period between 2006 to 2015 is summarized cumulatively as shown in table 1.

Table 1: Ten Years Reliability Indices of Transcorp Power Ltd, Ughelli

	2006			2007			2008			2009			2010		
Year	**Δ II**	**Δ III**	**Δ IV**	**Δ II**	**Δ III**	**Δ IV**	**Δ II**	**Δ III**	**Δ IV**	**Δ II**	**Δ III**	**Δ IV**	**Δ II**	**Δ III**	**Δ IV**
Number of failures	45	69	96	75	57	66	48	33	78	87	41	42	48	46	96
Downtime(h)	1415.25	3137.07	3548.55	1331.7	1068.06	3449.88	2754.9	2444.43	4302.9	1247.07	408.79	1861.14	603.9	839.38	2320.59
MTBF(h)	891.09	825.75	685.86	871.32	1598.13	844.17	932.48	1896.96	441.93	632.49	1797.01	1584.48	2540.52	2528.34	760.83
MTTR(h)	283.74	517.59	648.66	221.19	260.19	697.59	1053.27	1170.09	878.13	147.99	110.46	507.06	164.85	251.73	492.99
Repair rate, μ	0.00352	0.00193	0.00154	0.00452	0.00384	0.00143	0.00095	0.00085	0.00114	0.00676	0.00905	0.00197	0.00607	0.00397	0.00203
Failure Rate, F	0.0505	0.0836	0.14	0.0861	0.0357	0.0782	0.0515	0.0174	0.1765	0.1376	0.0228	0.0265	0.0189	0.0182	0.1262
Availability %	75.85	61.47	51.39	79.75	86.01	54.68	46.96	61.85	33.48	81.04	94.21	75.76	93.91	90.95	60.68
Reliability %	95.08	91.98	86.94	91.75	96.5	92.48	94.98	98.28	83.82	87.15	97.74	97.38	98.13	98.2	88.15

	2011			2012			2013			2014			2015		
Year	**Δ II**	**Δ III**	**Δ IV**	**Δ II**	**Δ III**	**Δ IV**	**Δ II**	**Δ III**	**Δ IV**	**Δ II**	**Δ III**	**Δ IV**	**Δ II**	**Δ III**	**Δ IV**
Number of failures	30	20	54	51	46	36	20	16	40	36	41	52	36	82	141
Downtime(h)	650.04	735.32	3864.9	1621.14	763.46	526.08	1382	289.08	986.32	693.16	707.88	698.58	2934.45	3540.12	1821.06
MTBF(h)	1736.4	2086.01	2513.5	1608.09	3798.96	2059.64	3701.22	794.64	789.84	632.72	1046.49	858.54	1574.22	2378.86	413.97
MTTR(h)	244.5	416.04	1170.93	470.34	833.67	1263.1	695.24	223.72	264.72	418.87	618.48	654.12	1080.15	1025.3	280.13
Repair rate, μ	0.00409	0.0024	0.00085	0.00213	0.0012	0.00079	0.00144	0.00447	0.00378	0.00239	0.00162	0.00153	0.00093	0.00098	0.00357
Failure Rate, F	0.0173	0.0096	0.0215	0.0317	0.0121	0.0175	0.0054	0.0201	0.0506	0.0569	0.0392	0.0606	0.0229	0.0345	0.3414
Availability %	87.66	83.37	68.22	77.37	82.01	61.99	84.19	78.03	74.9	60.17	62.85	56.76	59.31	69.88	59.73
Reliability %	98.29	99.05	97.87	96.88	98.8	98.27	99.46	98.01	95.06	94.47	96.16	94.12	97.94	96.61	71.08

4: Analysis and Discussion of Results

Table 1 present reliability indices for the gas turbines of Transcorp Power Ltd Ughelli from 2006 to 2015 according to their functional commissioning batches, Delta II, Delta III and Delta IV. Greater percentage of the recorded failures were attributed to excessive combustor temperature, faulty cooling water fan motor, faulty compressor bleed valve, exhaust over temperature, excitation trouble and generator differential lockout, low gas pressure or too much vibrations on the bearings.

In the years 2006, 2010 and 2015, Delta IV gas turbines witnessed frequent failures as a result of excessive exhaust flue gases temperature attributed to combustor problems, too frequent cleaning of fuel filters due to premature clogging of the filters caused by the supply of poor quality natural gas, and calibration issues of gauges monitoring flue gases pressure and temperature. In the year 2012 and 2013, the Delta IV turbines had the least failure rate and downtime which invariably improved its Reliability and Availability. This is because of a thorough planned maintenance carried out on its turbines and overhaul of its auxiliary equipment.

In 2015, Delta III major problems were system lubrication which is mainly the oil feeding pressure. If periodic inspection and replacement of worn out parts were done, the failure would have reduced, especially those for parts exposed to excessive heat and placed in the channels handling hot gases like the combustion chamber and turbine. Installation of sensing elements should be done to monitor vibrations of the bearings, pump pressures, oil flow properties and temperatures. In addition, planned maintenance should be carried out at least, once in two months to enable the monitoring of metallic debris in the lubricating fluids which is a sign of possible wear of bearing parts. The measure for durability and economical effectiveness of generating devises like gas turbine are the failure rate (F) and repair rate (μ).

4.1: Effect of Failure Rate on System Reliability and Availability

From figure 2, 3 and 4 below, failure rate (F) of Δ II peaked at 0.1376 in 2009 with Reliability (R_t) of 0.8715 (or 87.15%) and Availability of

0.8104 (or 81.04%) and recorded minimum Failure rate value of 0.0054 in 2013 with Reliability (R_t) of 0.9946 (or 99.46%) and Availability of 0.8419 (or 84.19%).

While for Δ III, maximum Failure rate value of 0.0836 was obtained in 2006 with Reliability (R_t) of 0.9198 (or 91.98%) and Availability of 0.6147 (or 61.47%) and minimum value of 0.0096 in 2011 with Reliability (R_t) of 0.9905 (or 99.057%) and Availability of 0.8337(or 83.37%).

Δ IV failure rate (F) peaked at 0.3414 in 2015 with system Reliability (R_t) of 0.7108 (or 71.08%) and system availability (A) of 0.5973 (or 59.73%) and its lowest value of 0.0175 was recorded in 2012 with Reliability (R_t) of 0.9827 (or 98.27%) and Availability of 0.6199(or 61.99%).

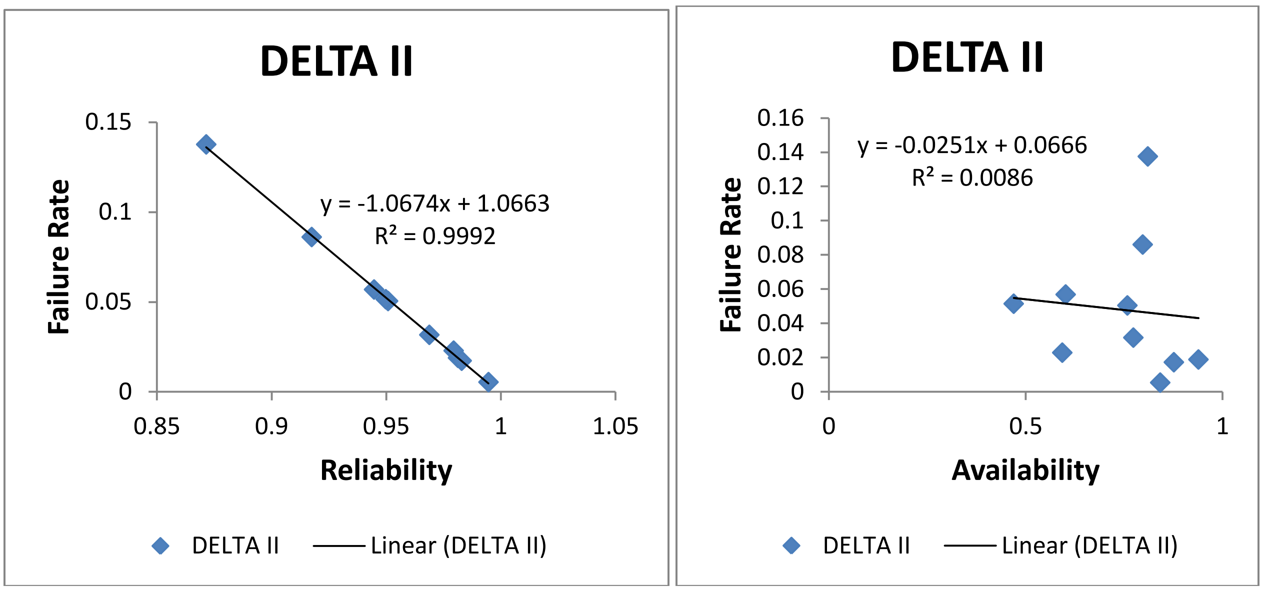


Figure 2: Effect of Failure Rate on System Reliability and Availability for Delta II Turbines

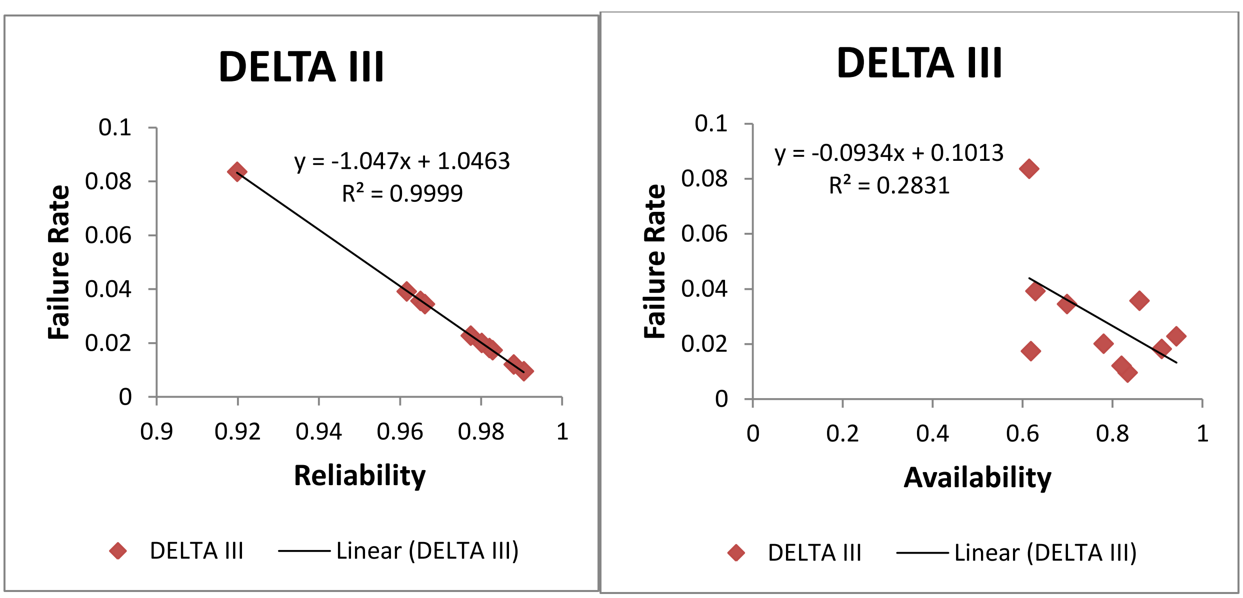


Figure 3: Effect of Failure Rate on System Reliability and Availability for Delta III Turbines

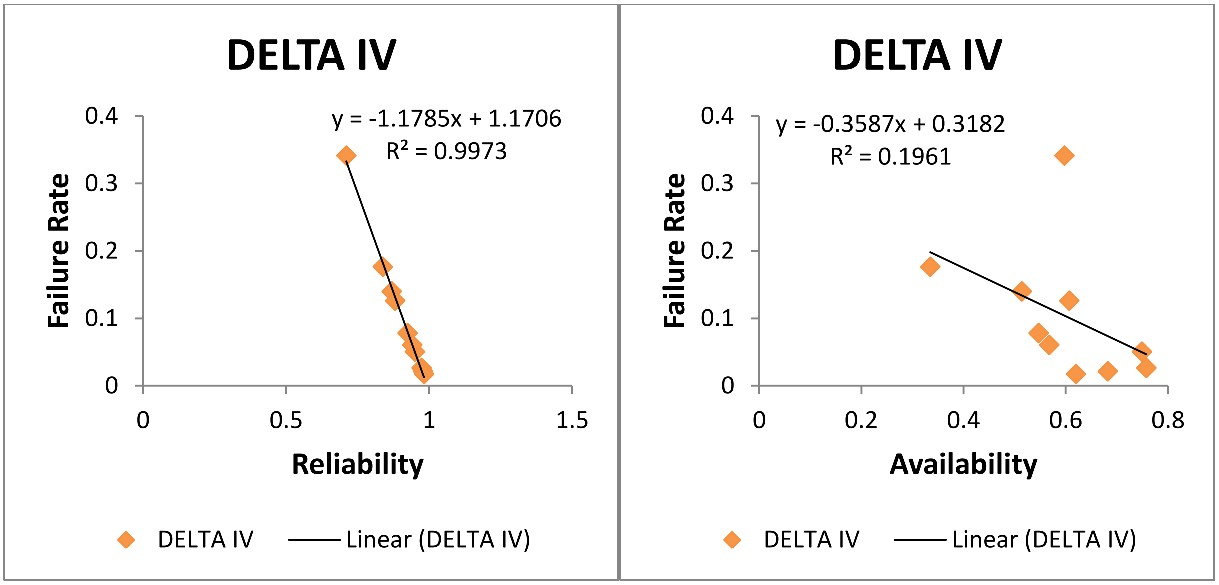


Figure 4: Effect of Failure Rate on System Reliability and Availability for Delta IV Turbines

The foregoing analyses reveal that increase in Failure rate (F) results to decrease in Reliability (R_t) and Availability (A), also decrease in failure rate results in increase in reliability and availability. Therefore, proper maintenance policy implementation is crucial in decreasing the hostile consequences of system failure. This can be obtained by precisely forecasting the systems' failure in such a way that remedial steps could be planned and executed so as to reduce the manner by which system failure affect operation. To avoid catastrophic and degradation failures, systems showing partial failure should be fixed before further usage.

4.2: Effect of Repair Rate (μ) on System Reliability and Availability

The effect of repair rate (μ) on Reliability (R_t) and Availability (A) are presented in Fig. 5 to 7. The charts show that Δ II gas turbines' repair rate was maximum (max μ) of 0.0068 in 2009 with Reliability (R_t) of 0.8715 (or 87.15%) and Availability (A) of 0.8104 (or 81.04%), and has its least repair rate (min μ) of 0.00093 2015 with Reliability of 0.9794 and Availability of 0.5931.

In the other hand, Δ III has max μ of 0.0091 in 2009 with Reliability of 0.9774 and Availability of 0.9421 and min μ of 0.00085 in 2008 with Reliability of 0.9828 and Availability of 0.6185. Also, Δ IV has max μ of 0.0038 in 2013 with Reliability of 0.9506 and Availability of 0.749 and min μ of 0.00079 in 2012 with Reliability of 0.9827 and Availability of 0.6199.

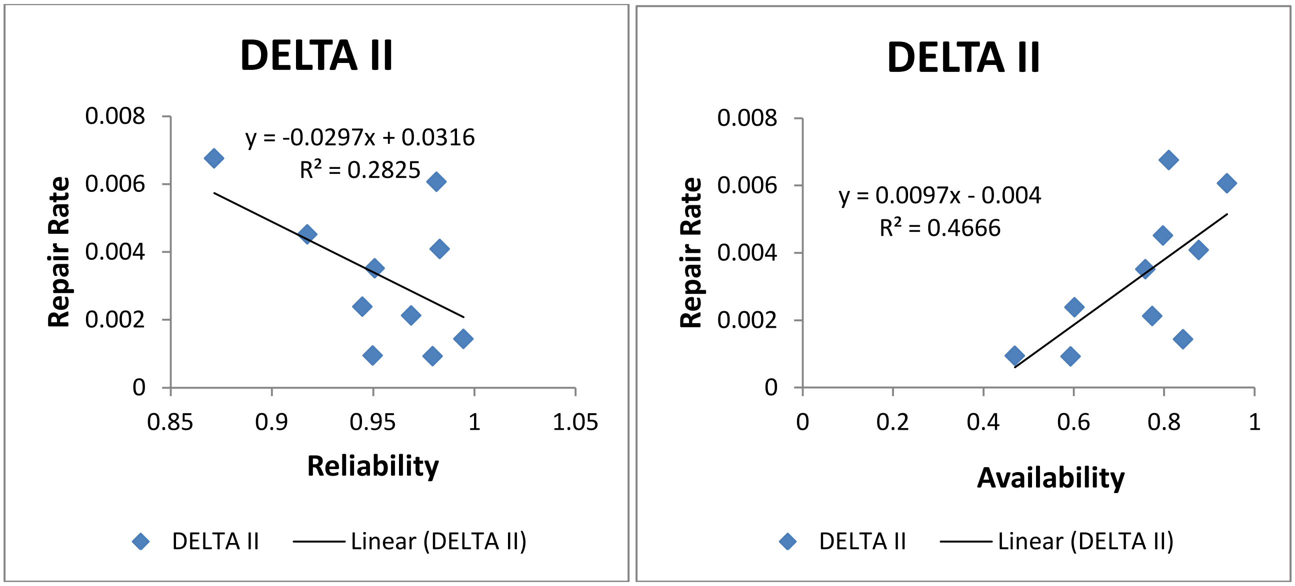


Figure 5: Effect of Repair Rate (μ) on System Reliability and Availability for Delta II Turbines

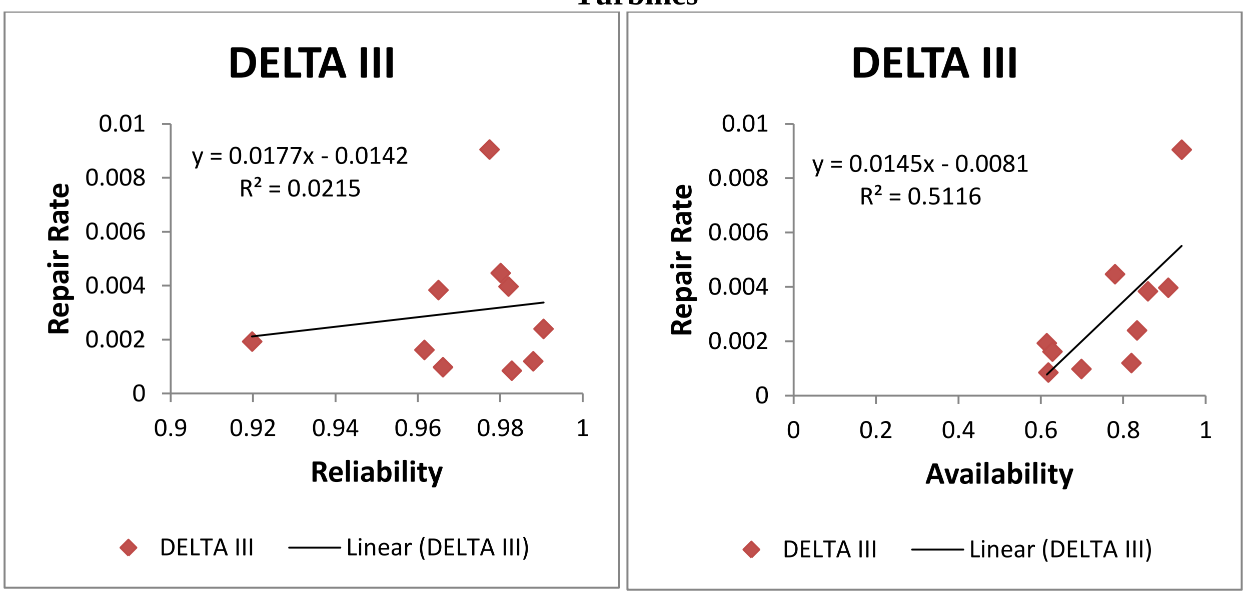
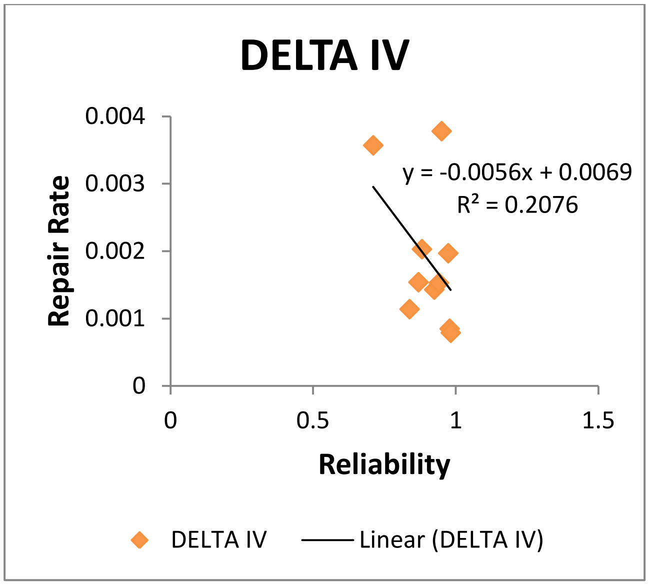


Figure 6: Effect of Repair Rate (μ) on System Reliability and Availability for Delta III Turbines



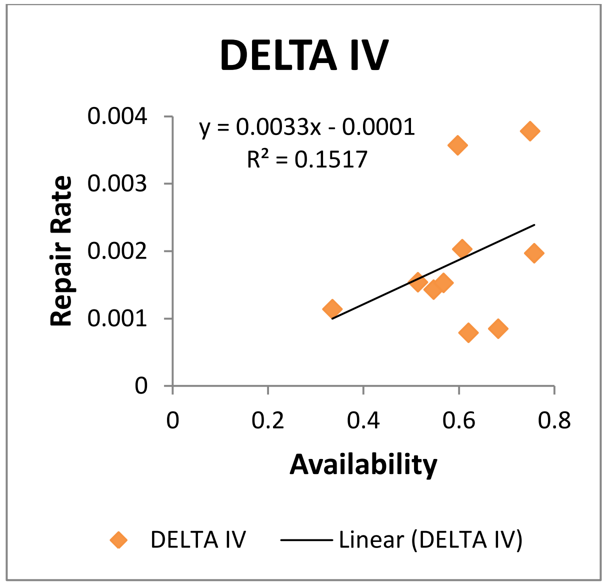


Figure 7: Effect of Repair Rate (μ) on System Reliability and Availability for Delta IV Turbines

The analyses above show that Reliability (R_t) decreases with increase in repair rate and increases with decrease in repair rate. Also, Availability (A) increases with increase in repair rate (μ) and decreases with decrease in repair rate.

5: Conclusions

Observations from the results and discussions have shown that increase in Failure rate (F) results in decrease in Reliability (R_t) and Availability (A), and decrease in failure rate results in increase in reliability and availability. The analyses also show that Reliability (R_t) decreases with increase in repair rate and increases with decrease in repair rate, while Availability (A) increases with increase in repair rate (μ) and decreases with decrease in repair rate.

From the analysis thus far, it is clear that the evaluation of reliability R(t) by extension, Availability (A) of the gas turbine power plants at Transcorp Power limited Ughelli is factored out by indices such as failure rate(F) and repair rate (μ).

The system availability values for the gas turbine station are lower than the IEEE recommended standard which is 0.999 or 99.9% and certain maintenance policies need to be enacted to reduce failure and its adverse effects.

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